

NILE DELTA BEACH PEBBLES II: ROUNDNESS AND SHAPE PARAMETERS AS INDICATORS OF MOVEMENT

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ABSTRACT

This paper discusses roundness, sphericity, flatness index, flatness ratio and elongation parameters of Nile Delta beach pebbles. Generally 1365 pebbles were analysed and a total of 12 285 measurements was done. Beach pebbles were measured for the main diameters, large inscribing circle and diameters of corners. Several indices were used to study the variations in the roundness and shape of pebbles. Three principal methods of evaluating roundness and two methods for sphericity are correlated in relation to their results.

Flatness index is more close to being the inverse of the maximum projection sphericity of SNEED, E. D. and FOLK, R. L. [1958] than the KRUMBEIN, W. C. [1941] measure. Beach pebbles show a significant change with decreasing size, they become well rounded, more spherical, less elongate and more flattened in shape.

On light of roundness, sphericity and other shape parameters, the relations to distance of transport along the coast are analysed. The increasing in roundness which accompanies the decreasing in sphericity and flatness points to beach pebbles abrasion as a main cause for movement along the coast. The increasing in flatness index and decreasing in elongation index of beach pebbles from the points of supply towards the east was so marked. Geometrically, this modification should take place by abrasion chiefly of both short and long axes with slightly different rates.

INTRODUCTION

Beach pebble is an unconsolidated, natural accumulation of rounded rock fragments resulting from erosion and consisting predominantly of particles larger than sand.

Early studies of beach pebbles were done by many authors. DUNN, E. J. [1911] observed that slate pebbles were discoidal and uniform-wearing rocks developed spherical forms. WENTWORTH, C. K. [1922] found that massive igneous rocks yielded flat pebbles on New England beaches. MARSHALL, P. [1928, 1930] concluded that beach pebbles were abraded flat by the sliding action of the surf or by the swash of finer material over them. LONDON, R. E. [1930] experimentally concluded that discs should accumulate high on the beach while the spheres should lie at the foot.

More recent works have been published and gave a great advance to the pebbles studies. CAILLEUX, A. [1945, 1947, 1952] studied the flatness of beach pebbles on varied rock types and related it to marine wear. SNEED, E. D. and FOLK, R. L. [1958] showed that sphericity depends most importantly on the inherent abrasional properties of the different rock types. On the basis of particle shape, BLUCK, B. J. [1967] subdivided the gravels of South Wales beaches into four zones and related these features to different settling velocities of different shape particles. KING, C. A. M., and BUCKLEY, J. T. [1968] succeeded to differentiate between Arctic environments by using flatness, roundness and sphericity. DOBKINS, J. E. and FOLK, R. L. [1970] mentioned

that roundness increases from river to beaches while sphericity decreases. They found also that wave height is crudely related to mean beach pebble roundness.

CARR, A. P. [1971] concluded that lateral movement of individual pebbles is not necessarily greater under storm conditions, and added that there is a relationship between pebble size and longshore movement. GOEDE, A. [1975] related the downstream changes in shape of pebbles of rhyodacite and sandstone in Tambo River to four main processes: abrasion, shape-sorting, dilution and breakage. ORFORD, J. D. [1975] concluded that the degree of shape zonation appears to be a function of wave energy conditions, with maximum pebble zonation appearing as a product of swell wave action. By using the axial ratio C/B of Sarmiento River and Pellegrini Lake, SPALLETTI, L. A. [1976] found that their values tend to increase with transport distance when the movement of particles is in traction, and to diminish in suspension.

This paper is a continuation to the previous studies of beach pebbles morphology along the coast. The main part includes the study of pebble roundness, sphericity and shape analysis to provide a body of basic data to be used in the study of sediment movement.

SAMPLING

Nile Delta beach pebbles located between 3 km west of Burullus outlet and 12 km east of Gamasa drain. They are continuous over distance of 75 km. To study the lateral variation in pebbles morphology, sampling sites were chosen at 3 km intervals (Fig. 1).

A total number of 1365 pebbles was measured along 26 localities. At each locality, a set of pebbles was collected by taking all pebbles within an area of 4 square meters to obtain a number of pebbles ranges from 62 to 75. At some localities, it

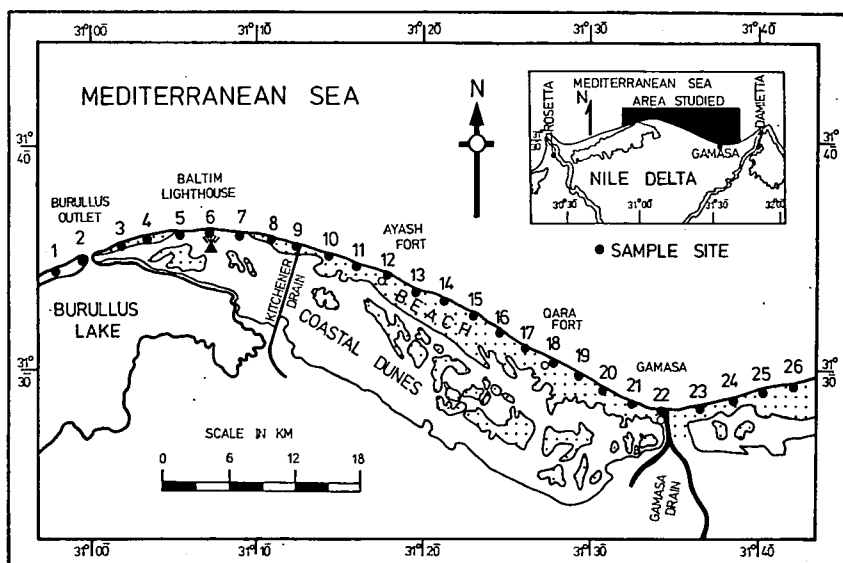


Fig. 1. Locality map showing sampling sites for Nile Delta beach pebbles.

was necessary to collect a few pebbles outside the considerable area to cover the occurred size classes within the locality.

Size classes, defined on the basis of the long dimension of the pebble were >256 mm, 256—128 mm, 128—64 mm, 64—32 mm, and 32—16 mm(>—8Ø, —8 to —7 Ø, —7 to —6 Ø, —6 to —5 Ø, and —5 to —4 Ø). In each size class, 10—25 pebbles were measured.

METHODS OF STUDY

Roundness: According to several authorities, roundness would be as follows:

WENTWORTH, C. K. [1922a]: $D_k/0.5(L+I)$

CAILLEUX, A. [1947]: D_k/L

WADDELL, H. [1933]: $\Sigma D_c/ND_i$

KUENEN, PH. H. [1956]: D_k/I

DOBKINS, J. E. and FOLK, R. L. [1970]: D_k/D_i

where: L: long axis of the pebble, I: intermediate axis, D_k : diameter of the sharpest corner, D_c : diameter of curvature of corners, D_i : diameter of the largest inscribed circle, N: number of corners.

Diameter of corners and largest inscribed circles are measured with a nest of concentric coloured circles duplicated on transparent plastic film. Circles are spaced logarithmically at the equivalent of quarter phi unit intervals. To measure the diameter of the corners, the largest inscribed circle and the axes, the pebble is laid flat on its maximum projection face. The last five measures for roundness are computed.

Sphericity: It is quantitative parameter measuring the departure of a body from equidimensionality. In other terms it measures the ratio between the three major dimensions of a particle. The three axes (L, I, S) of each pebble were measured according to the method suggested by KRUMBEIN, W. C. [1941]. In this paper, it was decided to use the following two famous sphericity methods:

KRUMBEIN, W. C. [1941]: $\sqrt[3]{IS/L^2}$

SNEED, E. D., and FOLK, R. L. [1958]: $\sqrt[3]{S^2/LI}$

In his evaluation of several sphericity indices, HUMBERT, F. L. [1968] found that the maximum projection sphericity of SNEED and FOLK [1958] was the most satisfactory in beach pebble studies.

Flatness ratio and flatness index: These two pebble shape parameters introduced by WENTWORTH, C. K. [1919, 1922a] in one of the first attempts to quantify pebble shape. They are given as:

Flatness ratio = $(L+I+S)/3$

Flatness index = $(L+I)/2S$

CAILLEUX, A. [1947, 1952] adopted the last measure change and is incorrectly called the Cailleux Index.

Elongation index: It was described by SCHNEIDERHÖHN, P. [1954] as the ratio of the greatest width to the greatest length (I/L). FOLK, R. L. [1968] suggested the least projection widths and lengths to be used. I/L and S/I are parameters used also by ZINGG, TH. [1935] to differentiate spherical and rods clasts from those of discoidal and bladed form.

(L—I)/(L—S) ratio: This measure was used by SNEED, E. D., and FOLK, R. L. [1958] in the sphericity-form diagram. The value $(L—I)/(L—S)$ defines whether the intermediate axis is closer in size to the short or to the long axis and as a result it gives three different shapes (platy, bladed and elongated).

Comparison of various roundness and sphericity measures:

Five measures for roundness have been computed; the roundness of WENTWORTH, C. K. [1922a], WADELL, H. [1933], CAILLEUX, A. [1947], KUENEN, PH. H. [1956], and DOBKINS, J. E. and FOLK, R. L. [1970]. Some of the last measures show great varieties while the others varying within a small range. For Nile Delta beach pebbles, it was found that the long axis (L) is generally larger than both the intermediate axis (I) and the diameter of the largest inscribing circle (D_i). On the other hand, (D_i) is close to (I) in most of pebbles. Logically, the roundness of WADELL, H. [1933] is the highest value because it depends on the average diameter of all corners. When the diameter of the sharpest corner (D_k) is dividing by the D_i , I, L, and $(L+I)/2$, it can be found that the roundness of DOBKINS and FOLK (the modern measure) is closely related to KUENEN measure, has small differences with WENTWORTH measure, and it is much higher than CAILLEUX measure. Table 1 shows the results of various measures related to DOBKINS and FOLK measure.

TABLE 1

Various roundness measures related to DOBKINS and FOLK [1970]

Measures	WENTWORTH (1922b)	WADELL (1933)	CAILLEUX (1947)	KUENEN (1956)	DOBKINS & FOLK (1970)
Average roundness	0.304	0.470	0.265	0.362	0.393
Percentage	77 %	120 %	67 %	92 %	100 %

The roundness of DOBKINS and FOLK runs about 8—23% higher than both of WENTWORTH and KUENEN, but 33% higher than that of CAILLEUX and it is big difference. It averages also 20% lower than that of WADELL. For this reason, the correlation may be made between the roundness of DOBKINS and FOLK, CAILLEUX (the lowest value) and WADELL (the highest value).

Two famous measures of sphericity were computed; KRUMBEIN, W. C. [1941] sphericity which modified from WADELL, H. [1934] and SNEED, E. D., and FOLK, R. L. [1958] sphericity. The maximum projection sphericity of SNEED and FOLK takes into consideration the hydraulic behaviour of the particle and therefore is a more actualistic concept of sphericity and preferred measure. The average sphericity for all pebbles according to SNEED and FOLK measure is 0.265, while it is 0.433 in the measure of KRUMBEIN. Thus, the maximum projection sphericity runs about 40% lower than that of KRUMBEIN measure.

Fig. 2 shows the mean roundness and sphericity for various measures along Nile Delta coast pebble beaches. Regarding the roundness, it is found that the three measures of WADELL, CAILLEUX, and DOBKINS and FOLK follow each other along the coast. With the direction of movement from west to east, the difference between WADELL and DOBKINS and FOLK roundness reduces gradually from 0.20 to 0.05. Such decreasing trend is due to the effect of abrasion which tends to reduce the corners of pebbles from four or more to two and the pebbles become more rounded. Nearly, CAILLEUX roundness keeping the same difference with the other two measures.

Considering the sphericity along the coast, it is observed that the maximum projection sphericity of SNEED and FOLK follows quite closely that of KRUMBEIN.

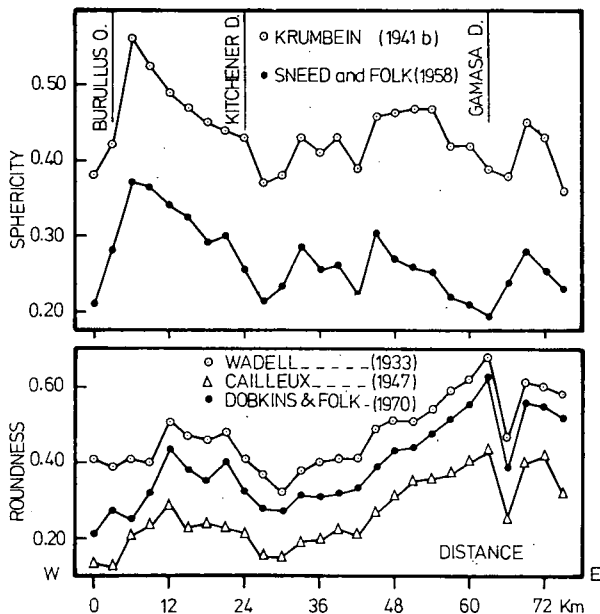


Fig. 2. Mean sphericity and roundness for various measures along Nile Delta pebble beaches.

(Fig. 2). The two measures show a wide difference which reflect the ratio between the main axes of pebble. Nile Delta beach pebbles are so flat because the short diameter is very small (32—2 mm) regarding to the other two diameters (300—12 mm). As a result of this, the maximum projection sphericity shows a high difference comparing to KRUMBEIN measure. But, however, by tracing the sphericity along the coast from west to east (Fig. 2), it is found that the difference between the two measures gradually increases from 0.15 to 0.20. This is because the pebbles become more flattend in shape near the eastern end of movement.

Correlation between couples of roundness and sphericity

The relations between couples of roundness for various measures [WADELL, H., 1933; CAILLEUX, A., 1947; DOBKINS, J. E., and FOLK, R. L., 1970] usually follow a positive correlations (Fig. 3A). In each relation the axes "X" and "Y" represent the mentioned first and second measure successively. Fig. 3A depends on both the mean roundness in each pebble class and the mean roundness for all pebbles on each locality. It is clearly seen in Fig. 3A that the relation couple of roundness follow a slight curved line and each couple keeps the same difference to the other. In other ways, it is reflecting the features of axes and mentioned that various measures of roundness are dependable populations. The same result could be seen in Fig. 3B where the relation between KRUMBEIN and SNEED and FOLK sphericities is drawn. In fact, such relationships can be used to convert both roundness and sphericity from one measure to the other depending upon the last two Figs.

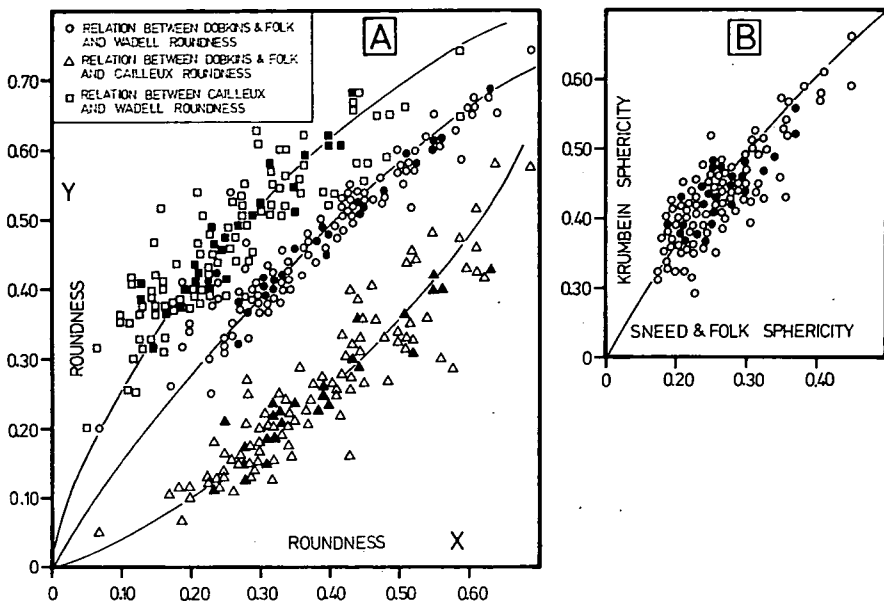


Fig. 3. Relation between couples of roundness (A) and couples of sphericity (B). White symbol represents the mean value in each pebble class while the black one represents the mean in each location.

Correlation between flatness index and sphericity

A plot was made of sphericity on each locality (using both measures of KRUMBEIN, W. C. [1941]; SNEED, E. D., and FOLK, R. L., [1958] versus flatness index of WENTWORTH, C. K. [1922 a]. The association between the values is shown in Fig. 4. The available data plot as curved line which means that the function is of the type $Y = bX^a$ where Y is the sphericity, X is the flatness index, a is coefficient

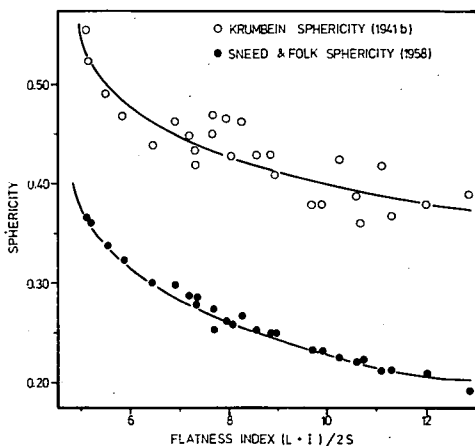


Fig. 4. Correlation between flatness index and sphericity measures.

and b is a constant. It is apparent that as the flatness index increases the sphericity decreases and the two values stood in inverse relations to each other. HUMBERT, F. L. [1968] and KING, C. A. M. and BUCKLEY, J. T. [1968] also noted the same relationship.

The negative correlation between KRUMBEIN sphericity and flatness index shows more individual deviation of values from the mean curved line (Fig. 4). On the other hand, the relation of SNEED and FOLK sphericity to flatness index represents a smooth curved line without deviations and the individual values are well spreaded along the curved line. The proposed measure of SNEED and FOLK "the maximum projection sphericity" takes into consideration the hydraulic behaviour of the particles. Therefore, this measure seems to be closely related to the flatness index which reflects the actual settling velocities of irregular particles in water. Thus, the flatness index came more close to the maximum projection sphericity than the KRUMBEIN measure which least reflects the hydraulic behaviour.

Sphericity-form diagram

Sphericity-form diagram was used to determine the form of Nile Delta beach pebbles. In order to make comparison between form and size of pebbles, Fig. 5 shows data distribution area for each size class. Beach pebbles larger than 256 mm are very significantly bladed to slightly elongated with lowest sphericity values. Pebbles with size 256—128 mm are completely bladed with higher sphericity values

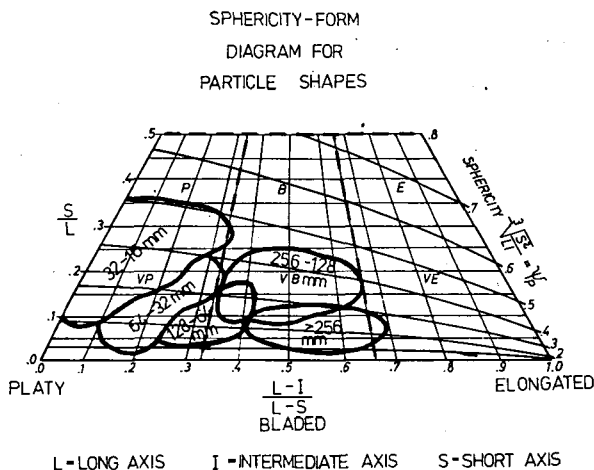


Fig. 5. Sphericity — form diagram for particle shapes. This triangle graph shows data distribution area for each mean pebble class in all localities.

than the largest size. All pebbles within the 128—64 mm range from slightly bladed to slightly platy but with sphericity values lower than the last size class. Smaller pebbles with size classes 64—32 mm and 32—16 mm show a distinct tendency to be more platy with an increasing in sphericity to attain the maximum values. Thus, the form changes are shown well in Fig. 5. With decreasing size, pebbles tend to change from slightly elongate or bladed to platy. In the same trend, pebbles become more spherical. Therefore, the form of Nile Delta beach pebbles is significantly a function of size.

Pebble size as a function to roundness and shape parameters

Nile Delta beach pebbles show a significant change of roundness, sphericity, flatness index, flatness ratio, elongation index and the platy — bladed — elongated ratio with size of pebbles. The results are illustrated in Table 2 and Figs 6 and 7.

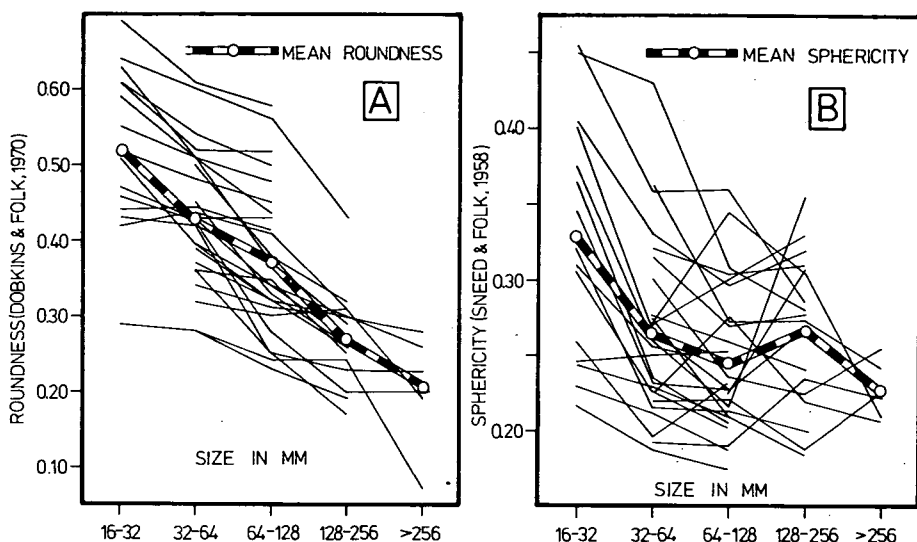


Fig. 6. Relation of roundness (A) and sphericity (B) to size of Nile Delta beach pebbles in each locality. Pebbles markedly increase in roundness with decreasing size. Smaller sizes tend to be more spherical than the larger ones.

TABLE 2

Mean roundness and shape parameters compared with size classes of beach pebbles

Size class in mm	Roundness	Sphericity	Flatness index	Flatness ratio (mm)	Elongation index	$\frac{(L-I)}{(L-S)}$
> 256	0.21	0.227	9.93	149	0.58	0.46
256—128	0.27	0.268	8.34	85	0.61	0.44
128—64	0.37	0.247	9.39	52	0.69	0.35
64—32	0.43	0.265	8.56	31	0.78	0.25
32—16	0.52	0.329	6.00	19	0.88	0.15

Size and roundness

Simply stated, the beach pebble populations markedly increase in roundness with decreasing size. Among the five size classes, beach pebbles larger than 256 mm show the worst rounding. As illustrated in Table 2 and shown in Fig 6A, the roundness of largest size ranges between 0.07 and 0.28 with an average of 0.21. With decreasing size, the roundness tends to increase gradually. The smallest pebbles 32—

16 mm show the best rounding. Their roundness value ranges between 0.29 and 0.69 with an average of 0.52. The majority of the individual lines, representing the change in roundness, behave with a lesser degree than the average line. In other words, the roundness increases very slowly but in some cases remains nearly constant.

Due to the action of approaching waves, pebbles according to their size show a certain tendency level of sliding and moving. As a result, each size attains a certain roundness value. The nearly straight line of mean roundness connected between size classes (*Fig. 6A*) may support such tendency. Small pebbles are easily sliding and for them the abrasion during movement is enough to produce well rounding corners and to reduce its number from four or more to one or two. The difference in roundness values within the size classes may represent also up-and-down drift pebbles and was assigned to the distance of transport.

Incomplete data from PETTUOHN, F. J. [1957] suggest that the coarsest fraction of outwash gravels (64—8 mm) was better rounded than the smallest size. But, in fact, the difference in roundness value between the gravel classes ranges between 0.06—0.09. Moreover, his roundness value for 32—16 mm compares closely with the mean value of smallest *Nile Delta beach pebbles* (0.52). In casual examination of Colorado River pebbles, SNEED, E. D. and FOLK, R. L. [1958] found an increase of roundness with increasing size. There exists a middle grain size of pebbles which shows the best rounding [KUENEN, PH. H., 1964; FÜCHTBAUER, H., and MÜLLER, G., 1970]. In Tahiti-Nui, DOBKINS, J. E., and FOLK, R. L. [1970] found that the smallest pebbles on sandy beaches are well rounded than that on a gravelly beaches, and generally the largest and smallest pebbles are less rounded.

Size and sphericity

Nile Delta beach pebbles show a sort of change of sphericity with size over the range from larger than 256 mm to 16 mm (*Fig. 6B*, Table 2). However, the difference between the average lowest and highest sphericity values of size classes is about 0.102, but the relation shows an increase in sphericity with decreasing size with the exception of size class 256—128 mm. Beach pebbles larger than 256 mm have the lowest mean sphericity value of 0.227 and range between 0.208 and 0.254. The smallest pebble size 32—16 mm ranges between 0.216 and 0.453 with an average of 0.329. Generally, Nile Delta beach pebbles show small size-to-size sphericity variation but greater pebble-to-pebble variation within each size class. So, regarding the relation between Nile Delta pebble size and both roundness and sphericity, it can be said that roundness well represent this relation and serves better than sphericity.

Little extensive study has been carried out in the relation between size and sphericity. PLUMLEY, W. J. [1948] found that 64—32 mm pebbles of limestone had higher sphericities than did 32—16 mm pebbles. CARROLL, D. [1951] found no significant change of sphericity with three size classes of sandstone pebbles. PETTUOHN, F. J. [1957] cites many examples of a sphericity increase with size, but they are examples taken from sand range. SNEED, E. D., and FOLK, R. L. [1958] noted the tendency for small pebbles to have higher sphericity than larger ones in Colorado River. DOBKINS, J. E., and FOLK, R. L. [1970] observed that the largest beach and river pebbles have the lowest sphericities. It now appears probable that the maximum of the sphericity *versus* size curve occurs in the coarse sand to granule range and that particles both coarser and finer than this have continually decreasing sphericity.

Flatness index, the first sphericity measure which suggested by WENTWORTH, C. K. [1922a], shows the same behaviour of maximum projection sphericity with relation to size. Flatness index decreases with decreasing size as shown in *Fig. 7A*.

A drop in flatness index is observed for the pebble size 256—128 mm, this drop is reflected also by the sphericity measure. Flatness index and sphericity stood in inverse relations to each other as shown in Fig. 7A; as the flatness index decreases sphericity increases.

Flatness ratio is one of the first attempts to quantify pebble shape and was introduced by WENTWORTH, C. K. [1919]. The relation between flatness ratio and size shows a fantastic decreasing trend (Fig. 7B). A smooth curved line connected between size classes can be shown. Flatness ratio decreases gradually with decreasing size without any drop. The individual curves also show the same picture and there is no overlapping in the flatness values for the different size classes. Thus, flatness ratio can be used to differentiate well between size classes of Nile Delta beach pebbles.

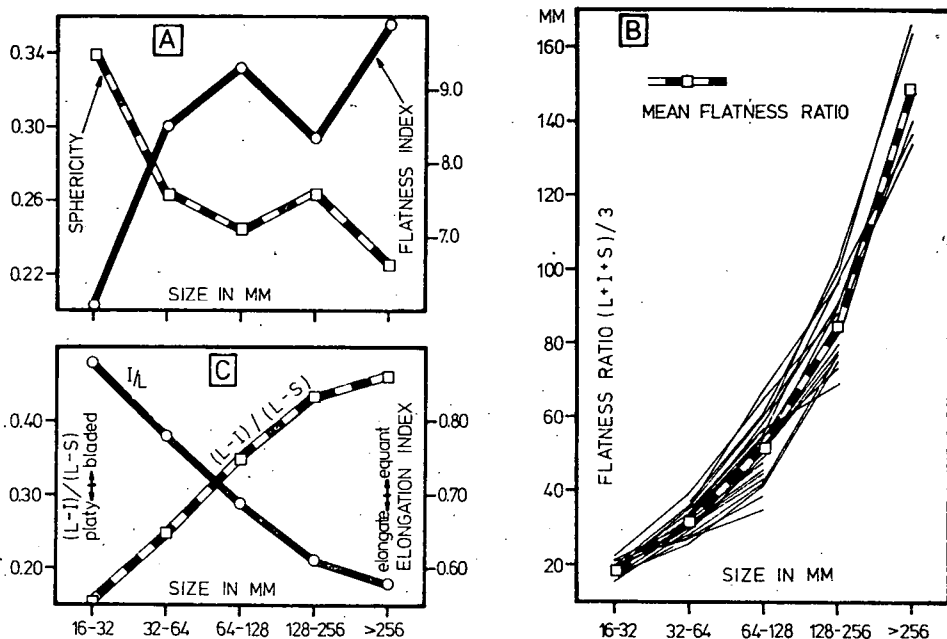


Fig. 7. Relations of shape parameters to size of Nile Delta beach pebbles. A — Sphericity and flatness index. B — Flatness ratio. C — Elongation index (I/L) and $(L-I)/(L-S)$ value.

Size and pebble elongation

Two formulae can be used to describe the elongation of beach pebbles. The first formula is $(L-I)/(L-S)$ value which classifies the form of pebbles to platy, bladed and elongated. The second formula is the elongated index (I/L) which gives three main classes: equant, intermediate and elongate.

Nile Delta beach pebbles show marked difference in the $(L-I)/(L-S)$ value with size as shown in Fig. 7C. There is a great tendency for the pebbles to change from bladed to platy with decreasing size. However, the difference between the two larger classes is small, but the mean value decreases directly with constant rate toward the smallest pebble size.

The same relation is observed between the elongation index (I/L) and size.

There is a regular increasing in the elongation index with decreasing size. In other words, larger pebbles tend to be elongated while the smaller ones tend to be equant or less elongated (Fig. 7C).

A scatter plot between $(L-I)/(L-S)$ value and (I/L) shows that there is a linear relationship between the two parameters and they are inversely reflected the same description of elongation trend of beach pebbles. Although elongation index is independent upon the short axis of pebbles, it gives also the same features regarding to $(L-I)/(L-S)$ value. In fact, this is an indication to the highly flatness of Nile Delta beach pebbles.

Characteristic features of beach pebbles

The relation between pebble size and roundness, sphericity and other shape parameters is not usually random, but it follows a sort of decreasing or increasing trend. Such change is shown as a function of selective abrasion effect among different size population and depends on the distance of transport.

Nile Delta beach pebbles are generally flattened in shape, nearly with the same composition (sand + silt + clay) without any tendency to partings. On the other hand, they show a wide variety in size ($>256-16$ mm). So, the selective abrasion of beach pebbles depends on size and hydrodynamic factors affecting the movement of pebbles. Wave heights of about 80 cm are average for Nile Delta coast. During the storm season, the average wave heights are 130 cm with maxima never exceed 300 cm. Littoral current generally feeds from west to east with an average velocity of 80 cm/sec [MANOHAR, M. 1976]. Thus, the significant change of pebble parameters with size can be related directly to the effect of hydrodynamic factors. Due to the action of approaching waves, the beach pebbles show some varieties according to their effect. It is thought that wave heights have not the ability to move all sizes with the same degree. Therefore, for each pebble size there is a certain tendency level of moving and as a result certain features.

For the smallest beach pebbles, they have the highest mean roundness and sphericity, lowest flatness ratio, and highest elongation index. Of course, small pebbles are easily washed by current and gentle waves which can apparently slide and bounce them randomly to obtain their characteristic features. On the other hand, larger pebbles show the lowest mean roundness and sphericity, highest flatness ratio, and lowest elongation index. PETTJOHN, F. J. [1957] mentioned that the larger pieces are most readily rounded. But local materials of coarse grain may not be as well rounded as the finer far-travelled materials. Of course, these differences were assigned to differences in distance of transport. It was observed that larger beach pebbles were concentrated only in three restricted areas along Nile Delta coast. So, the larger pebbles are not always in motion because hydrodynamic factors are often insufficient to move them enough up-and-down the beach face and also to a long distance. Thus, larger pebbles do not well rounded.

Pebbles movement and its relation to roundness, sphericity, flatness and elongation index

An investigation has been made to analyse the movement direction of pebbles along 75 km stretch of Nile Delta coast. What started out as a simple study of roundness and shape parameters of beach pebbles has become very complex. This is largely due to the presence of three secondary sources, variable influence of hydrodynamic factors affecting the coast and the influence of pebble size. The results are illustrated in Table 3 and Figs 8 through 10.

TABLE 3

Mean roundness, sphericity and other shape parameters along the coast

Localities	Sampling site no.	Roundness	Sphericity	Flatness index	Flatness ratio (cm)	Elongation index	$(L-I)/(L-S)$
0.0 km	1	0.21	0.210	11.98	7.99	0.69	0.32
3.0	2	0.28	0.282	7.28	10.20	0.61	0.44
6.0	3	0.25	0.368	5.08	5.31	0.85	0.18
9.0	4	0.32	0.364	5.14	5.26	0.77	0.29
12.0	5	0.44	0.338	5.50	4.67	0.73	0.32
15.0	6	0.38	0.326	5.85	4.53	0.69	0.37
18.0	7	0.35	0.290	7.20	5.64	0.72	0.33
21.0	8	0.40	0.303	6.46	5.47	0.65	0.40
24.0	9	0.32	0.255	8.54	6.28	0.74	0.30
27.0	10	0.28	0.214	11.30	7.67	0.65	0.38
30.0	11	0.27	0.234	9.67	8.35	0.63	0.40
33.0	12	0.31	0.285	7.29	7.65	0.67	0.38
36.0	13	0.31	0.254	8.95	8.25	0.67	0.37
39.0	14	0.32	0.261	8.01	5.39	0.74	0.30
42.0	15	0.33	0.223	10.63	5.25	0.70	0.34
45.0	16	0.39	0.303	6.91	4.51	0.74	0.31
48.0	17	0.43	0.269	8.25	3.47	0.82	0.21
51.0	18	0.44	0.262	7.97	3.30	0.85	0.18
54.0	19	0.48	0.252	7.64	3.25	0.83	0.19
57.0	20	0.51	0.226	10.25	3.17	0.80	0.22
60.0	21	0.55	0.209	11.12	3.14	0.85	0.17
63.0	22	0.63	0.193	12.83	2.88	0.80	0.21
66.0	23	0.39	0.237	9.88	4.05	0.62	0.42
69.0	24	0.56	0.278	7.67	4.22	0.77	0.25
72.0	25	0.55	0.249	8.91	3.15	0.75	0.28
75.0	26	0.52	0.227	10.70	2.68	0.59	0.44

Roundness and movement

All size classes of Nile Delta beach pebbles show a definite though fluctuating increase in both mean and individual roundness for each class. *Fig. 8A* shows the lateral variation of roundness along 26 sampling sites.

East of Burullus outlet, the initial mean roundness is 0.21, it increases laterally eastwards and rapidly attains its maximum value of 0.44 at locality 12 km. The area east and west of Kitchener drain characterized by decreasing of roundness. Eastward of locality 27 km (*Fig. 8A*), there is a significant increasing in roundness. It tends to increase gradually and attains its maximum value of 0.63 at Gamasa coast. A drop of roundness was observed for all pebble sizes just east of Gamasa but it tends to increase again eastwards. Theoretically, by progressive abrasion, pebbles would be more rounded with a value of 1.0, but actually such value is never reached. The maximum roundness value was found to be 0.69 for the smallest size class 32—16 mm. PETTJOHN, F. J. [1957] related this phenomenon to the inhomogeneities in the material and to the rigor of the abrasive process. Between Burullus outlet and Kitchener drain,

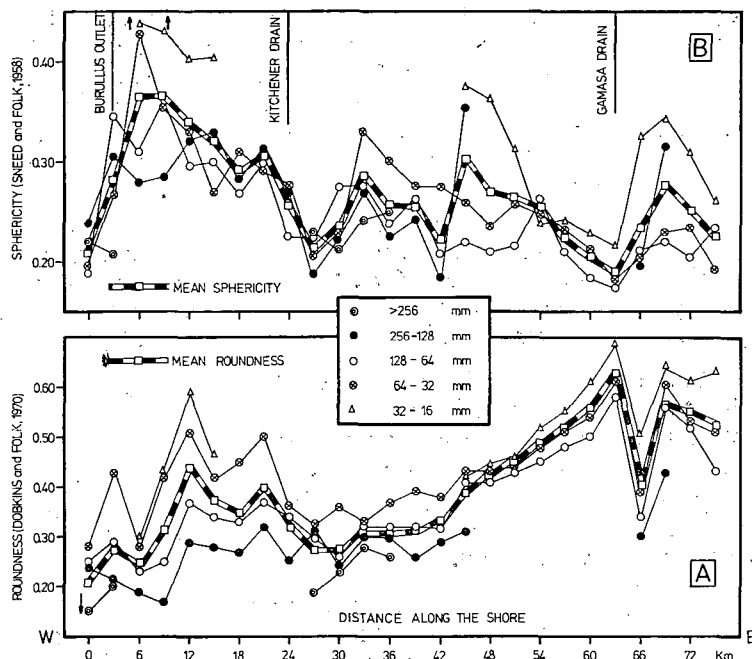


Fig. 8. Lateral variations of roundness (A) and sphericity (B) of beach pebbles along Nile Delta coast.

Nile Delta beach pebbles show high size-to-size roundness variation. But eastwards, the rest of the coast shows a small variation and the difference reduced to a minimum value. By tracing the roundness for each pebble size class as shown in Fig. 8A, it is clear that pebbles are arranged according to their size. Larger pebbles are less rounded than the smaller ones because they are not always in motion.

East of Burullus outlet, roundness changes most rapidly at first and more slowly later between Kitchener and Gamasa drains. Table 4 illustrates the main differences in rate of roundness between up-and-down drift localities. It is clearly observed from this table, with the exception of pebbles larger than 256 mm, that the rate of variation

TABLE 4

Rate of roundness improvement for pebbles at up-and-down drift localities along Nile Delta coast

size class	up-drift between 0—12 km	down-drift between 30—63 km
>256 mm	0.130	0.023
256—128 mm	0.011	0.011
128—64 mm	0.032	0.026
64—32 mm	0.120	0.022
32—16 mm	0.150	0.027
average rate	0.089	0.021

increases with decreasing size at both up-and-down drift localities. Smaller beach pebbles introduced in up-drift localities round more rapidly than the larger ones, but progressively more slowly thereafter. These results agree with all previous work that pebble rounding proceeds rapidly at first and then slows down to approach some asymptotic limit (WENTWORTH, C. K. 1919, 1922a; KRUMBEIN, W. C., 1941, 1942; GROGAN, R. M., 1945; PLUMLEY, W. J., 1948; VAN ANDEL, T. J. H. *et al.*, 1954; KUENEN, PH. H., 1956; SNEED, E. D., and FOLK, R. L. 1958].

Beach pebbles that were collected astride Burullus outlet and just east of both Kitchener and Gamasa drains show the worst roundness comparing with the other areas. These three drops in roundness (*Fig. 8A*) could be seen for all pebble sizes. The corners of pebbles are somewhat sharp and show more than four corners. Some concluding remarks are given below concerning the movement of beach pebbles:

1. The three drops in roundness indicate pebbles coming from source areas owing to their worst roundness.
2. Eastward of each drop, there is a significant improvement in roundness due to the general west-east longshore drift.
3. It may be noted that there is a certain similarity between the pebbles of the three secondary sources from the point of pebble size, roundness, and shape parameters (see later).

The preliminary conclusion is that the movement of beach pebbles just west of Kitchener and east of Gamasa drains is not simple as it can be from Kitchener to Gamasa drains. In fact, it is influenced by the supplying of pebbles from the secondary sources. Therefore, the roundness is so marked at these areas. The rapid rate of pebble supplying has not allowed roundness development to occur yet at these drops. But during movement of pebbles along the coast from west to east, they show better roundness. As far as it can be derived from tracing of roundness, pebbles are actively moving eastwards from Kitchener to Gamasa drains. Such active motion, which follows the eastward drift, is certainly responsible for the regular and excellent improvement in roundness.

Sphericity and movement

Simply stated, there is a general decrease in sphericity with the direction of movement along the coast. *Fig. 8B* shows lateral variation of sphericity of beach pebbles with distance of transport. West of Burullus outlet, the initial sphericity is very low. For size classes, it ranges between 0.191 and 0.236 with an average of 0.210. For a short distance of transport (9 km), beach pebbles become more spherical. It is clearly observed that small pebbles attain the maximum sphericity value (0.453) more rapidly than larger ones (0.281). Eastwards of locality 9 km, size classes of pebbles show a decreasing trend in both mean and individual sphericity with definite fluctuations. *Fig. 8B* clearly shows that smallest size always have the higher sphericity.

Tracing of sphericity along the coast reveals the same situations as in roundness. Some pebble beaches show a definite high sphericity differences between size classes, while the others show a significant small differences. These variations could be related to the secondary sources of beach pebbles. At the three secondary sources, there are small differences in sphericity of size classes. Eastward of each locality, these differences become higher owing to sphericity variation during movement on the basis of size classes. Therefore, the up-drift localities (west of Burullus outlet, just east of Kitchener and Gamasa drains) show small size-to-size sphericity variation.

On the other hand, the down-drift localities (i.e. the localities 6, 33, 45 and 69 km, Fig. 8B) show the reverse.

Flatness index for beach pebbles shows the same behaviour of sphericity along the coast (Fig. 9A), but the two parameters stood in inverse relations as mentioned before. East of Burullus outlet, flatness index decreases sharply at first and then tends to increase gradually to Kitchener drain. Eastwards, it decreases with some fluctuations and thereafter increases gradually to attain its maximum value at Gamasa coast. The last figure indicates that the small pebbles always have the small flatness index values. Studies carried out by WENTWORTH, C. K. [1922b] and CAILLEUX, A. [1947,

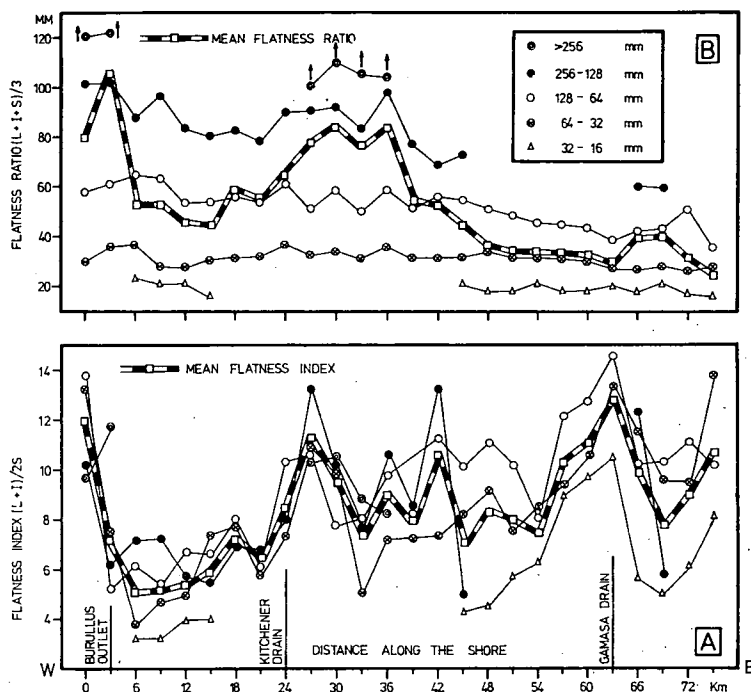


Fig. 9. Lateral variations of flatness index (A) and flatness ratio (B) of beach pebbles along Nile Delta coast.

1952] mentioned that, however, the flatness of pebbles is strongly influenced by the source material, beach pebbles become less flat, hence acquire a higher sphericity with prolonged wear. But this phenomenon can be observed only on the first 6 km of transport path.

As mentioned before, the flatness ratio $(L+I+S)/3$ decreases steadily with decreasing pebble size. This phenomenon can be observed also in Fig. 9B where flatness ratio for each size is drawn versus the distance along the coast. Mean flatness ratio shows a rapid decreasing trend east of Burullus outlet. Just east of Kitchener drain a peak is observed due to feeding the coast by newly pebbles from source area. Eastward of this peak, there is a gradual decreasing in flatness ratio. It is clearly observed from Fig. 9B that the rate of decreasing is higher between Kitchener and Gamasa drains.

To sum up, Nile Delta beach pebbles show a general decreasing in sphericity accompanied with increasing in flatness index and decreasing in flatness ratio during movement along the coast. This could be caused either by actual abrasion toward a disc-like form, or by shape-sorting.

Whether or not beach pebbles show a progressive increase in sphericity with transport is an unsettled problem. In fact, the final shape that any pebble acquires, by abrasion during transport, is essentially dependent upon the initial shape liberated from bedrock, composition, hardness, inherited partings, size, mode, agent and rigor of transport. A well-bedded sediment with well-developed fissility and cleavage possesses the tendency to produce tabular and elongated pebbles, whereas massive rocks tend to produce spherical pebbles. Regarding to Nile Delta beach pebbles, it is believed that they are derived from well-bedded submarine banks located NW and NE off Burullus headlands. Therefore, they attain low sphericities and are flattened in shape. Data from SNEED, E. D., and FOLK, R. L. [1958] show that rock type controls sphericity of Colorado River pebbles. The sphericity of quartz increases slowly downstream, but the sphericity of chert decreases markedly because chert pebbles split preferentially parallel with bedding.

The mode and medium of transport and transporting agents can affect the form of pebbles. Generally, it is said that beach pebbles tend to be flatter than those of rivers [CAILLEUX, A., 1945; KUENEN, PH. H., 1964]. Therefore, there is a difference in the process of abrasion that leads to increase in sphericity with prolonged fluvial transport (SNEED, E. D., and FOLK, R. L., 1958] and decrease in sphericity with prolonged beach abrasion. According to the evidences of increasing flatness and decreasing sphericity of Nile Delta beach pebbles during movement, it can be mentioned that these pebbles could be transported only with the smooth moving of their maximum projection face over the sandy bottom of nearshore zone. Such mode of moving reduces the short axis of pebbles to a higher degree rather than the other axes. Beach pebble shape is affected strongly by substrate character; whether sandy or gravelly beach. DOBKINS, J. E., and FOLK, R. L. [1970] mentioned that beaches that are dominantly gravel, where pebbles seldom move, have higher sphericities than the other sandy beaches. This may explain the low sphericity of Nile Delta beach pebbles.

Elongation and movement

The elongation index (I/L) and $(L-I)/(L-S)$ value were used for tracing pebbles movement along the coast. *Fig. 10* shows the variation of these two parameters with the distance of transport. Although (I/L) and $(L-I)/(L-S)$ stood in inverse relations to each other, it is clearly observed from the last figure that the two parameters gave the same result and behaviour. Near Burullus outlet, there is a rapid change in the elongation of pebbles. Generally, beach pebbles tend to change from bladed or slightly elongate to platy or equant. Just west of Kitchener and east of Gamasa drains, the beach pebbles seem to be elongated in shape owing to the feeding from source areas. From Kitchener to Gamasa drains, there is a gradual tendency for the pebbles to be more platy and this is probably due to the active motion of pebbles without confusion from the source area. The change of pebbles from bladed to platy can be caused only by wearing the long axis more than the intermediate one. It is also observed from *Fig. 10* that the larger pebbles (>256 mm and $256-128$ mm) show somewhat a weak trend to be more elongated with prolonged transport. This is the type of wear that should occur if the pebbles were rolled like a rolling pin with wear mainly on the intermediate axis. Beach pebbles with size $128-64$ mm follow

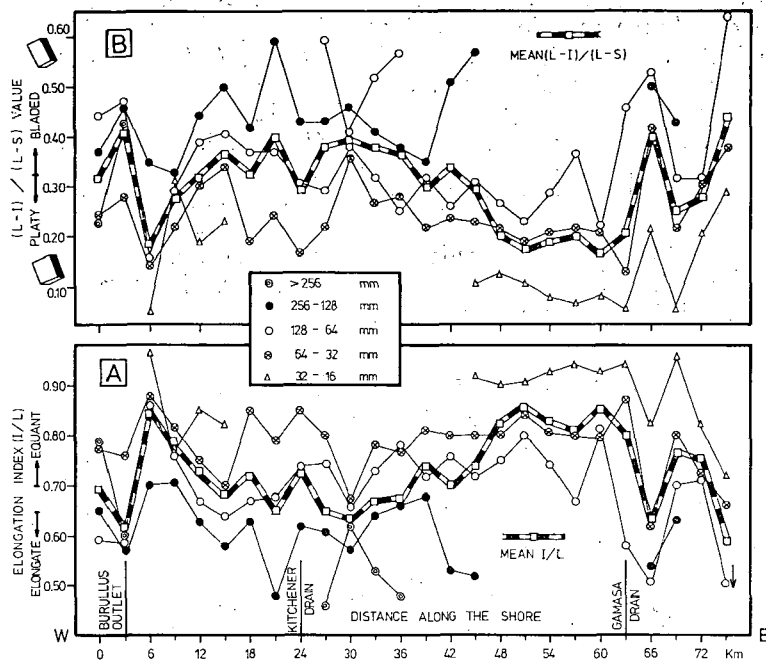


Fig. 10. Lateral variation of elongation parameters of beach pebbles along Nile Delta coast. A — Elongation index (I/L). B — The value (L-I)/(L-S).

quite closely the mean values of (I/L) and (L-I)/(L-S) along the shore and show a higher rate of variation to be platy in form.

Generally, larger pebbles show lower elongation index than the smaller ones. There is a strong selective tendency for the intermediate axis of larger pebbles to lie halfway between long and short axes to produce bladed forms. On the other hand, the intermediate axis is closer to the long axis for smaller pebbles to produce platy forms. Large and small pebbles show difference in their behaviour during the course of transport. Beach pebbles larger than 128 mm (Fig. 10) tend to be more elongate while the smaller ones tend to be more platy. Such difference in shape may be related to the effect of selective wearing on different size classes.

Results of abrasion and movement

Various parameters of beach pebbles are not equally affected during their movement. It was found that rounding and flatness ratio proceed more rapidly and serve better than the other parameters. As a result of movement, roundness increases, sphericity decreases and pebbles become more flat and platy in shape due to the change in the three main axes. Such change related to the effect of abrasion and not to the shape-sorting. The abundance of Nile Delta beach discs is due to the ease of sliding by surf action on a smooth sandy surface which makes abrasional flattening occurs more effectively.

It was found that several combinations of last parameters are effective in differentiation between pebbles from up-and-down drift localities. By plotting round-

ness versus sphericity, flatness ratio and elongation index (Fig. 11), it is possible to determine exactly the behaviour of pebbles during the path that beach pebbles follow. The combination of roundness versus sphericity (Fig. 11A) shows that down-drift pebbles become more rounded than the up-drift ones. On the same time sphericity is not effective and shows very weak correlation with roundness. Roundness versus elongation index shows a positive correlation (Fig. 11B). Down-drift pebbles tend to be much rounded and less elongate in shape (equant) while the up-drift ones tend to be less rounded and range from slightly equant to elongate in shape. Roundness versus flatness ratio (Fig. 11C) is most effective and shows a negative correlation between them. Up-drift pebbles are less rounded and have higher flatness ratio than the down-drift pebbles. Generally pebble population markedly increases in roundness and decreases in flatness ratio as it passes from large to small sizes.

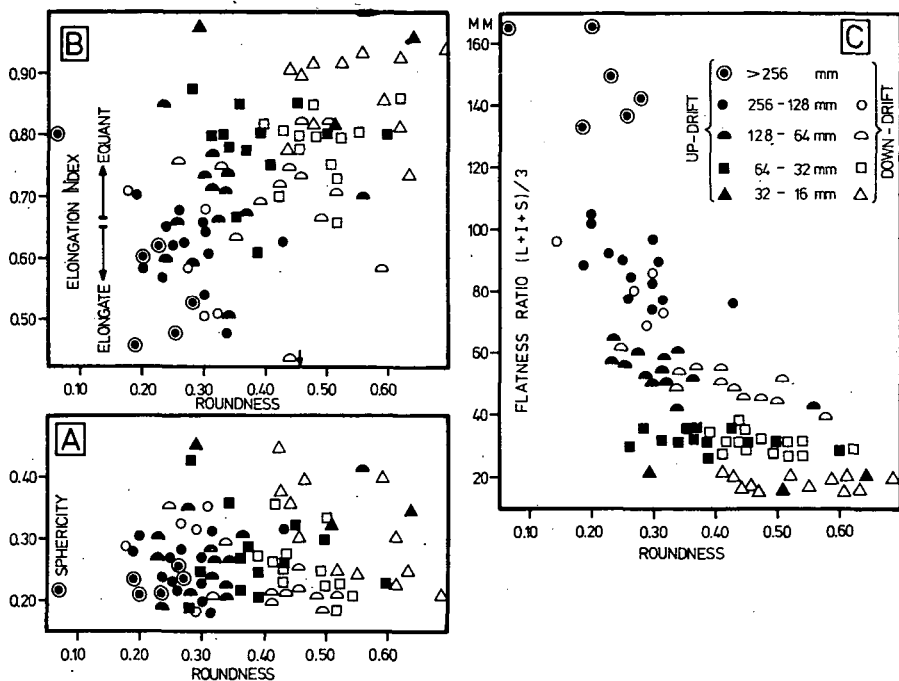


Fig. 11. Relation between up-and-down drift beach pebbles.

- A — Roundness vs sphericity.
- B — Roundness vs elongation index.
- C — Roundness vs flatness ratio.

By examining the relative changes of the three axes that take place during the movement, it could be concluded that pebbles as they move down-drift must suffer most wear on short axes as fast as long axes. This modification causing them to become less bladed and more platy. As a result, their sphericity shows a slight decrease during movement. It is possible also to assume that littoral current carrying beach pebbles will drop the large with elongate-shaped pebbles near up-drift before it drops the smaller and platy-shaped ones near down-drift.

SUMMARY AND CONCLUSION

The study of Nile Delta beach pebbles along 75 km leads to the following results:

1. Roundness measures of WADELL, H. [1934], CAILLEUX, A. [1947] and DOBKINS, J. E. and FOLK, R. L. [1970] follow quite closely each other along pebble beaches with considerable differences. A new method for evaluating roundness have to take into consideration to avoid the complexity of various measurements and to compare easily between pebbles from different environments.
2. The maximum projection sphericity of SNEED, E. D. and FOLK, R. L. (1958) shows lower values comparing to KRUMBEIN, W. C. [1941] measure although the two lines parallell each other along the coast. This difference related to the flaty features of Nile Delta beach pebbles.
3. Flatness index, which reflects the actual settling velocities of irregular particles in water, and sphericity measures stood in inverse relations to each other. Maximum projection sphericity is closely related to flatness index because it takes into consideration the hydraulic behaviour of particles more than KRUMBEIN measure.
4. Roundness and shape parameters are significantly functions of size. Beach pebbles markedly increase in roundness, slightly in sphericity and decrease in flatness index and flatness ratio with decreasing size. Pebbles tend to change from slightly elongate or bladed to platy form with decreasing size. Small pebbles are easily washed by gentle waves and currents which can apparently slide them more easily than larger pebbles.
5. Beach pebbles are derived mainly from west. The difference in roundness and shape parameters are so marked at three areas along the coast. The rapid rate of supply of pebbles has not allow shaping development to occur yet in these areas which can be considered as secondary source areas.
6. The processes of beach pebbles movement from the source area give rise to a progressive improve of roundness, decrease of sphericity and modification of shape parameters. These changes proceed rapidly at first and then slow down and agree with all previous work. Smaller beach pebbles introduced in up-drift localities round more rapidly than the larger ones but progressively more slowly thereafter.
7. Beach pebbles are actively moving from Kitchener to Gamasa drains. This active motion, which follows the eastward drift is certainly responsible for the regular and excellent modification in roundness and shape. Rounding proceeds more rapidly than sphericity, therefore it serves better as an indicator to the movement of beach pebbles.
8. Nile Delta beach pebbles show a significant form change with movement. The pebbles tend to be less spherical with high flatness index which paints to abrasion of the short axes. The pebbles change from elongate-bladed to platy form which geometrically should take by abrasion chiefly of the long axes. Therefore, such change related to the effect of abrasion and not to the shape-sorting.
9. The abundance of discs along Nile Delta coast may be related to the original structure of source area and dynamics factors. The ease of up-and-down slow motion of pebbles on their maximum projection area makes abrasional flattening occurs more effectively.

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Manuscript received, May 15, 1981

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